

RECENT QCD STUDIES AT THE TEVATRON

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Abstract

Since the beginning of Run II at the Fermilab Tevatron, the QCD physics groups of the CDF and DØ experiments have worked to reach unprecedented levels of precision for many QCD observables. Thanks to the large dataset - over 3 fb^{-1} of integrated luminosity recorded by each experiment - many important new measurements have recently been made public and will be summarized in this paper.

1 Introduction

The Tevatron collider at Fermilab provides collisions of protons with anti-protons at a center of mass energy of 1.96 TeV. This is currently the highest energy collider in the world. The multipurpose detectors of the CDF ¹⁾ and DØ ²⁾ experiments are exploiting the more than 3 fb^{-1} of integrated luminosity provided by the Tevatron in order to make important progress in constraining and confirming the calculations made from quantum chromodynamics (QCD).

Precise measurements of QCD observables in hadron-hadron collisions - such as jet cross sections - constrain parton density functions (PDFs) and confirm the predictive power of theory. This results in a better control of the standard QCD production calculations which are used to predict major backgrounds for many important physical processes. In addition, the specific QCD processes which pose challenges to new physics searches such as supersymmetry and Higgs production can be measured directly with dedicated analyses.

In this paper some of the most recent measurements from the CDF and DØ collaborations will be reviewed. These measurements will be split into underlying event observables, jet cross sections, and boson plus jet cross section measurements.

2 Hadronic Collisions and Underlying Event Observables

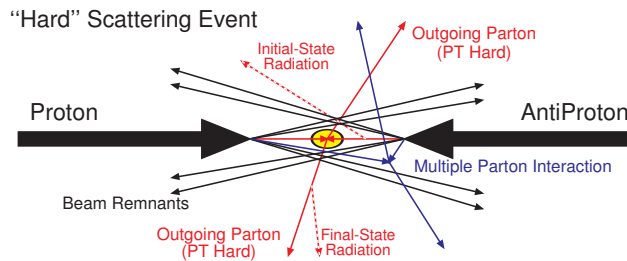


Figure 1: *Simple model for hadronic collisions.*

A brief introduction into the structure of hadronic collisions is useful as a motivation for jet definition. Hadronic collisions may be factorized into perturbative components (hard scattering and initial and final state radiation) and non-perturbative components (beam remnants and multiple parton interactions). These components are illustrated in the simple “cartoon” shown in

figure 1. This simple picture is similar to the model used by a program like PYTHIA ³⁾ to generate hadronic collisions.

Figure 1 should be thought of as occurring within the radius of the proton around the colliding partons. In fact, the picture becomes more complicated when the property of QCD color confinement and detector effects are included. The colored partons must hadronize into color neutral hadrons. All of these particles originating from the different components of the collider event are indistinguishable in the detector, and it is the job of jet algorithms to cluster these objects into jets. Figure 2 illustrates that jets may be clustered at the parton (quarks and gluons) or particle (hadrons) level when dealing with MC simulation, or detector (calorimeter towers) levels. Of course, measurements are made at the detector level, but it is useful to use the the parton and particle level jets from MC studies to derive corrections for the measured quantities.

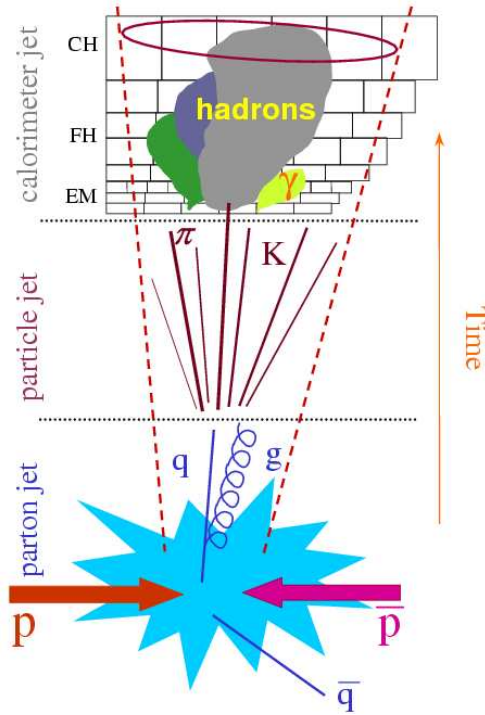


Figure 2: *Jets clustering can be defined at the parton, particle, and detector levels.*

Most results discussed in this note will focus on the properties of the perturbative component of the collision. However, studies of the “underlying event”^{4, 5)} from CDF focus on measuring observables that are sensitive to the non-perturbative components such as beam remnants and multiple parton interactions. These studies provide constraints useful for the modeling of the non-perturbative regime (where pQCD fails), such as the “soft” interactions generating the underlying event which accompanies the “hard” collision.

The direction of the leading calorimeter jet is used to isolate regions of η - ϕ space that are sensitive to the underlying event. As illustrated in figure 3, the direction of the leading jet, jet#1, is used to define correlations in the azimuthal angle, $\Delta\phi$. The angle $\Delta\phi = \phi - \phi_{\text{jet}\#1}$ is the relative azimuthal angle between a charged particle (or a calorimeter tower) and the direction of jet#1. The “transverse” region is perpendicular to the plane of the hard 2-to-2 scattering and is therefore very sensitive to the “underlying event”. These regions can be studied for different event topologies such as leading jet (require one or more jets), back-to-back (requiring two or more jets with the leading jets back-to-back in ϕ), and exclusive dijet (requiring only two jets which are back-to-back in ϕ). By studying different regions and event topologies components of the hadronic collision can be isolated.

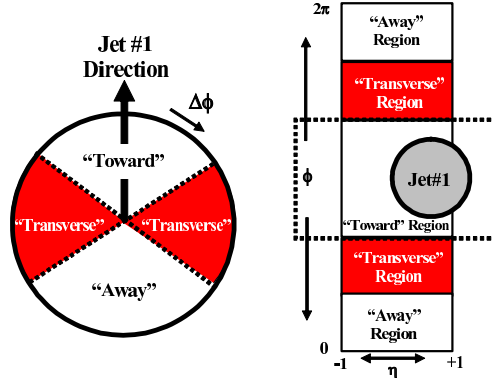


Figure 3: *Illustration of correlations in azimuthal angle ϕ relative to the direction of the leading jet in the event. Observables studied in the “transverse” region are sensitive the “underlying event”.*

CDF has recently updated their UE studies for leading jet events and other event topologies are under study. As an example of the types of observables measured, the charged particle density per unit η - ϕ in the toward, away, and transverse regions is shown in figure 4. The goal is to publish more than

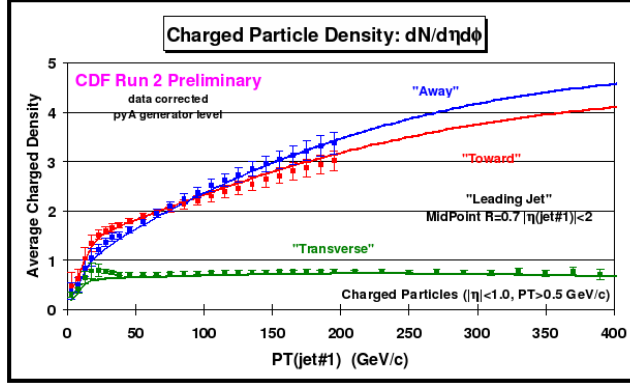


Figure 4: The charged particle density per unit $\eta - \phi$ in the toward, away, and transverse regions. The points are the data corrected to the particle level and the lines are the PYTHIA prediction for each distribution.

one hundred distributions of observables corrected to the particle level. These results will be useful for tuning and improving theoretical models of hadronic collisions. Understanding the underlying event contribution to jet events is important for many searches at the Large Hadron Collider (LHC) and measurements of this type will likely be of the first made at the LHC ^{6, 7}).

3 Jet Cross Section Measurements

3.1 Inclusive Jet Cross Sections

The measurement of the differential inclusive jet cross section at the Tevatron probes the highest momentum transfers in particle collisions, and thus is potentially sensitive to new physics such as quark substructure ⁸). The measurement also provides a fundamental test of predictions of perturbative quantum chromodynamics (pQCD) ^{9, 10}). Comparisons of the measured cross section with pQCD predictions provide constraints on the parton distribution function (PDF) of the (anti)proton, in particular at high momentum fraction ($x \gtrsim 0.3$) where the gluon distribution is poorly constrained ¹¹). Further constraints on the gluon distribution at high x will contribute to reduced uncertainties on theoretical predictions of many interesting physics processes both for experiments at the Tevatron and for future experiments at the LHC. Extending the measurements to higher rapidities significantly increases the kinematic reach

in the x - Q space, where Q denotes the momentum transfer, and helps to place stronger constraints on the gluon PDF.

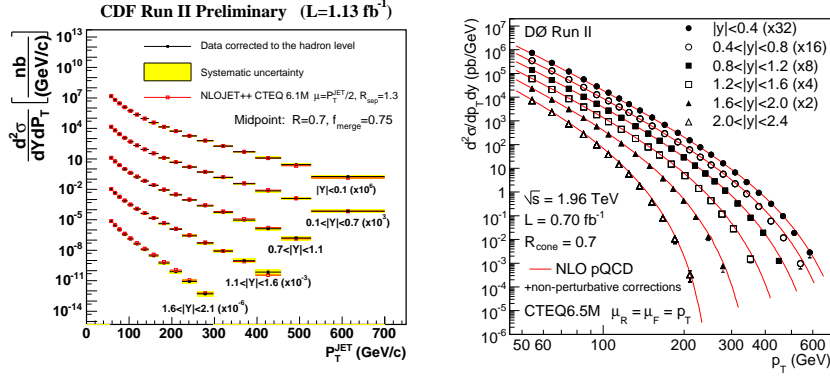


Figure 5: The inclusive jet cross section distributions recently measured by CDF (left) and DØ (right) using the Midpoint cone-jet clustering algorithm.

The inclusive jet cross section has been measured in Run II by CDF 12, 13) and DØ 14). The most recent measurements using the Midpoint cone jet clustering algorithm are shown in figure 5. The CDF result (left) compares with NLO predictions using CTEQ6.1M PDFs and 1.1 fb^{-1} of luminosity and breaks the measurement into five rapidity regions with $|y| < 2.1$, while the DØ result (right) compares with CTEQ6.5M 15) using 0.7 fb^{-1} of luminosity and splits the rapidity into six regions with $|y| < 2.4$. The comparison with NLO pQCD is shown by taking the ratio (DATA/THEORY) in figures 6 and 7. Both measurements observe reasonable agreement with the NLO predictions and see similar trends in the data at high rapidities. In addition the systematic uncertainties are smaller than the PDF uncertainty on the theory prediction and they should therefore be useful to constrain the proton PDFs. DØ recently reduced their absolute jet energy scale uncertainty - which yields the dominant systematic uncertainty in this measurement - to less than 2 %, and this improvement will lead to important constraints on the gluon PDF. These results are also reasonably consistent with the recently published CDF measurement 16) using the k_T clustering algorithm 17) pointing to the conclusion that the k_T -type algorithm can work well in the difficult hadron collider environment.

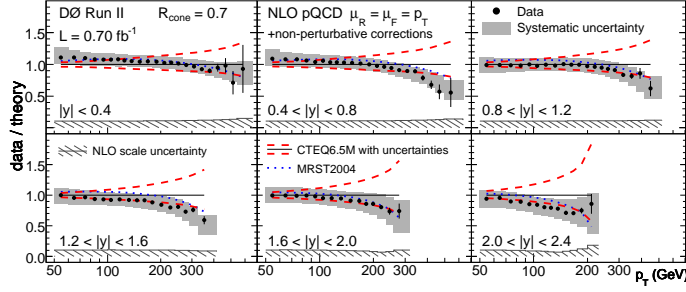


Figure 6: *The inclusive jet cross section ratios to the NLO pQCD predictions from DØ using the Midpoint cone-jet clustering algorithm.*

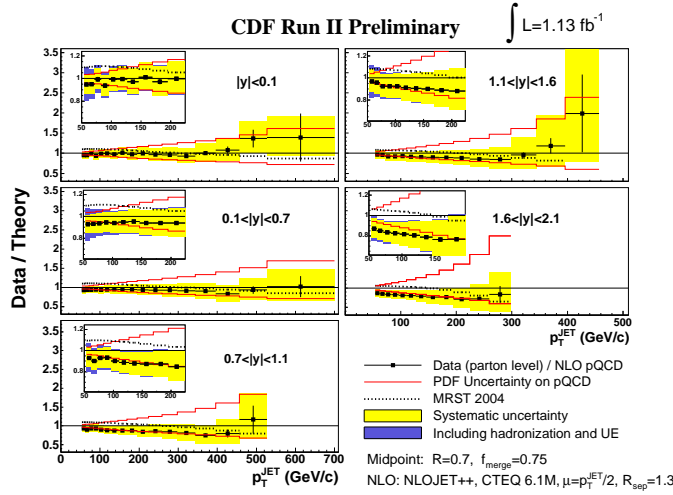


Figure 7: *The inclusive jet cross section ratios to the NLO pQCD predictions from CDF using the Midpoint cone-jet clustering algorithm.*

3.2 Dijet Mass

In addition to being a fundamental test of pQCD which can be used to constrain PDFs, the dijet mass (M_{jj}) cross section distribution can be used to constrain new physics models which predict heavy particles decaying to dijets. A recent measurement from CDF of the high dijet mass production cross section for $180 < M_{jj} < 1350 \text{ GeV}/c^2$ uses 1.1 fb^{-1} of luminosity. As shown in figure 8 nice agreement with the NLO predictions of NLOJET++¹⁸⁾.

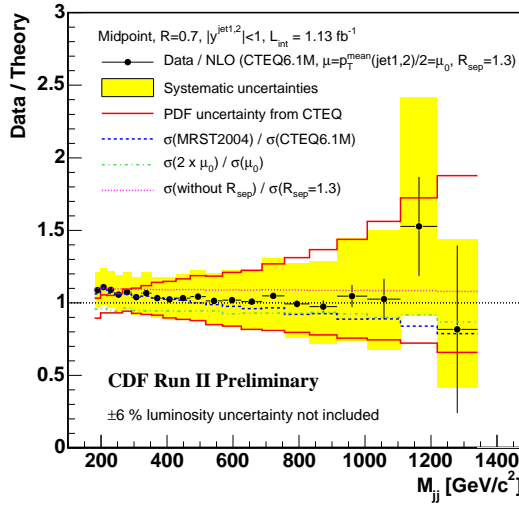


Figure 8: The dijet mass cross section ratio to the NLO pQCD prediction from CDF using the Midpoint cone-jet clustering algorithm.

3.3 Exclusive Dijets

In another exciting measurement the first observation of exclusive dijet production has been reported by CDF¹⁹⁾. In this analysis the presence of exclusively produced dijets ($p + \bar{p} \rightarrow \bar{p}' + 2jets + p'$) was demonstrated by studying the distributions of the dijet mass fraction, defined as the dijet mass divided by the full system mass. The dijet mass fraction distributions and the exclusive dijet mass differential cross section distribution are given in figure 9.

This exclusive dijet result is important because it verifies that theoretical calculations^{20, 21)} have control over exclusive production channels like the

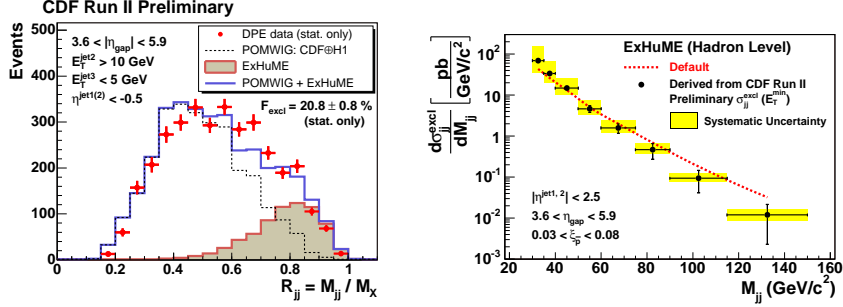


Figure 9: The Dijet mass fraction (left) and the exclusive dijet mass differential cross section distribution (right).

ones shown in figure 10. The exclusive Higgs boson production mechanism provides an exciting discovery possibility for the LHC and this exclusive dijet cross section measurement serves as a useful calibration channel for this process.

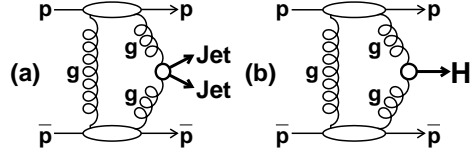


Figure 10: Production diagrams for exclusive dijet (a) and exclusive Higgs production (b).

4 Boson Plus Jet Measurements

Boson plus jet production processes measured at the Tevatron experiments are useful to study pQCD and in addition are some of the most important backgrounds in new physics searches. The most recent results for γ plus jet, Z plus jet, and W plus jet cross sections are presented next.

4.1 Triple Differential $\gamma + \text{Jet}$ Cross Section

Historically, inclusive direct photon cross section measurements have observed mediocre agreement with theoretical predictions (22, 23, 24). Recently, DØ

has measured the triple differential $\gamma + \text{jet}$ cross section ($\frac{d^3\sigma}{dp_T^\gamma d\eta^\gamma d\eta^{\text{jet}}}$) in an effort to understand these discrepancies (25). The analysis requires a photon in the central region ($|\eta| < 1.0$) with $p_T > 30 \text{ GeV}/c$ and a jet in the central ($|\eta| < 0.8$) or forward ($1.5 < |\eta| < 2.5$) region with $p_T > 15 \text{ GeV}/c$. The cross section measurement is then made in four distinct kinematic regions:

- Region1: Jet and γ in the central region and on the same side.
- Region2: Forward jet and central γ in the central region and on the same side.
- Region3: Jet and γ in the central region and on the opposite side.
- Region4: Forward jet and central γ on opposite sides.

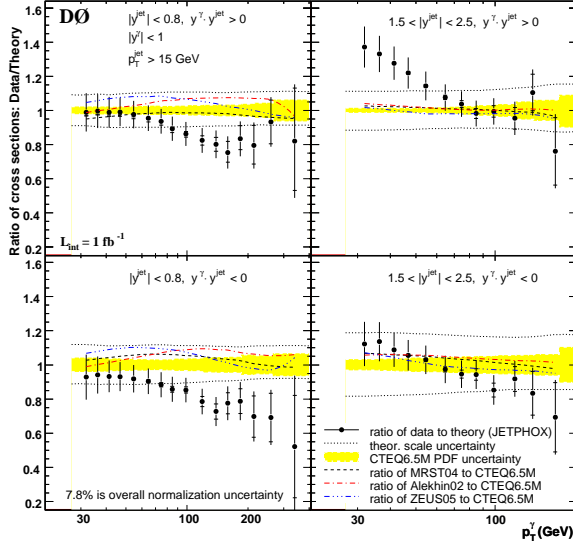


Figure 11: *Measured cross section to the NLO theory prediction is shown for each kinematic region.*

The ratio of measured cross section to the NLO theory prediction is shown in figure 11. This measurement extends the x and Q range significantly over previous measurements. In many regions the measured values are outside of the PDF uncertainty bands (CTEQ6.1). In addition, it is clear from the figure

that a simple theoretical scale variation cannot bring data and theory into agreement in all four regions. It should also be noted that the central region results are consistent with previous measurements from UA2, CDF, and DØ.

In addition to the ratios to theoretical predictions, ratios were taken between the different regions. In these ratios systematic uncertainties on the ratio largely cancel out and total experimental uncertainty is less than 9 %. The results of these studies are that shapes are reproduced by theory reasonably well, but there is a quantitative disagreement.

4.2 Z plus Jet Cross Sections

Z plus jet production provides a test of the properties of pQCD and this process is the dominant background for many supersymmetric searches. CDF has recently used di-electron final states to measure the inclusive jet cross sections in events with a Z/γ^* (26). Figure 12 shows the jet p_T distributions for ≥ 1 and ≥ 2 jets (left) and N-jet distributions (right). Good agreement is observed with the NLO predictions. The ratio to leading order shown in the N-jet study reveals that the LO-NLO “k-factor” does not exhibit strong dependence on the number of jets.

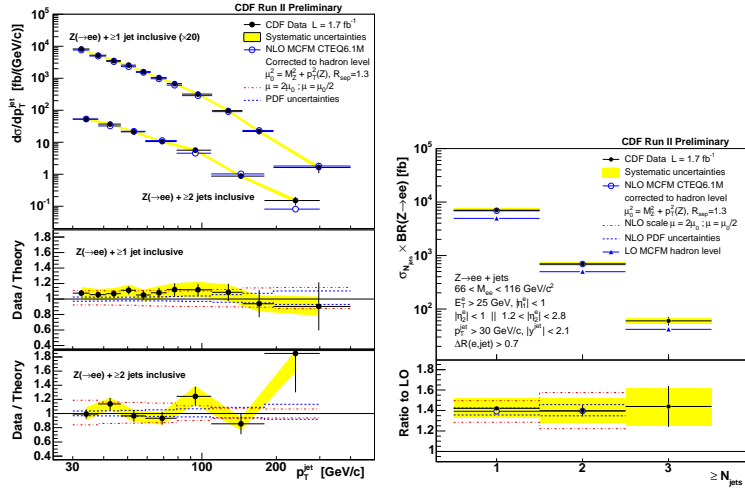


Figure 12: Results of the measurement of the Z plus jet cross section as a function of jet p_T (left) and number of jets (right).

Using di-lepton (e or μ) final states CDF has also recently measured the Z plus b -jet cross section. This measurement probes the heavy flavor content

	CDF Data	PYTHIA	ALPGEN	NLO +U.E+hadr.
$\sigma(Z + b\text{-jet})$	$0.86 \pm 0.14 \pm 0.12 \text{ pb}$	—	—	0.53 pb
$\sigma(Z + b\text{-jet})/\sigma(Z)$	$0.336 \pm 0.053 \pm 0.041\%$	0.35%	0.21%	0.23 %
$\sigma(Z + b\text{-jet})/\sigma(Z + \text{jet})$	$2.11 \pm 0.33 \pm 0.34\%$	2.18%	1.45%	1.71%

Table 1: The measured cross section and cross section ratios of Z plus b -jet to inclusive Z and Z plus jet cross sections as well as theoretical predictions for these quantities from PYTHIA, ALPGEN, and MCFM ²⁷⁾ with corrections for UE and hadronization affects.

of the proton and is an important background for singly produced top quark, ZH , and supersymmetric Higgs searches. For this analysis the invariant mass distribution for tracks pointing to a displaced vertex is used to separate b , c , and light quark contributions to the Z plus jet events. In table 1 the measured cross section and cross section ratios of Z plus b -jet to inclusive Z and Z plus jet cross sections are shown.

4.3 W plus Jet Cross Sections

W plus c -jet production is an important background for supersymmetric top quark and Higgs production. In addition the measurement of its cross section tests the s -quark content of the proton. Recently DØ measured this cross section and found reasonable agreement with the ALPGEN ²⁸⁾ prediction ^{29, 30)}. W plus b -jet production is the dominant background for single top quark and WH searches. Using a displaced vertex mass fit, CDF measured the cross section for W plus b -jet events with an electron or muon of $p_T > 20 \text{ GeV}/c$ and $|\eta| < 1.1$, missing transverse energy greater than 25 GeV, and one or more b -tagged jets with $p_T > 20 \text{ GeV}/c$ and $|\eta| < 2.0$. The result is $\sigma_{W+b\text{-jets}} \times Br(W \rightarrow l\nu) = 2.74 \pm 0.27(stat) \pm 0.42(syst) \text{ pb}$. This measurement should provide useful constraints to the W boson plus b -jet backgrounds for many future searches.

5 QCD Conclusions

Measurements from the Tevatron Run II are defining a new level of QCD precision measurements in hadron-hadron collisions. In this note many results from the Tevatron's rich program in QCD studies have been reviewed including: jet cross sections, W +jets, Z +jets, γ +jets and more. The recent inclusive jet cross section measurements from CDF and DØ report nice agreement with NLO predictions and observe similar trends in the data-theory comparison. Boson plus jet and boson plus heavy flavor cross sections are being measured. These

measurements are important for tests of pQCD and they also provide important constraints they provide on important backgrounds for new physics searches for supersymmetry and the Higgs boson. To summarize, the QCD programs of the CDF and DØ experiments are dedicated to testing and constraining pQCD and also measuring cross sections of important background processes. This important effort will continue to produce improved results as the Tevatron data sample continues to grow, so stay tuned.

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